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Determination of Effective Thoracic Mass

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16. Abstract

Effective thoracic mass is a critical parameter in specifying mathematical and mechanical models (such as crash dummies) of humans exposed to impact conditions. A method is developed using a numerical optimizer to determine effective thoracic mass (and mass distribution) given a number of acceleration signals and a force signal response. Utilizing previously reported lateral and frontal tests with human cadaveric test specimens in a number of different conditions, the effective thoracic mass is computed. The effective thoracic masses are then computed for a variety of crash dummies exposed to identical test conditions.

The force responses generated using the computed effective thoracic masses are compared to the actual measured force responses. The thoracic mass of the crash dummies is then compared to the values for human cadaveric subjects. The distribution of thoracic mass is found to be a function of test condition. The implications in terms of mathematical model development, crash dummy design, and the appropriateness of various types of tests (e.g. pendulum vs. sled) are discussed.

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DETERMINATION OF EFFECTIVE THORACIC MASS

INTRODUCTION

The effective mass of thoracic components is important to such critical issues as the biofidelity of proposed crash dummies. Debate related to the proper crash dummy to use frequently revolves around the issue of effective thoracic mass. In addition, computer models with incorrect effective masses will produce answers that differ from results found in real crashes. If a lumped parameter computer model, such as the model proposed by Lobdell, et al. (1972, 1973), is used to simulate a system of interest, such as the thorax in the case of the Lobdell model, the effective mass of each lumped mass in the model has a profound effect on the predictions of the model. While it is generally recognized that effective mass is an essential property, little has been written on the correct effective mass properties of the human thorax.

In this study, effective mass is defined as a constant property which when multiplied by the second time derivative of displacement (i.e., acceleration) yields the force resulting from an impact. It is important to understand that effective mass may not necessarily be determined solely from the static mass properties of a component of a system.

A method for determining effective thoracic mass is proposed based on performing a force balance on the thorax with dynamic data obtained during an impact event. Using this system, a number of tests from the National Highway Traffic Safety Administration's (NHTSA) Biomechanics Data Base are analyzed, and the resulting effective mass presented. The results of this analysis are then compared to available computer models, and to several different crash test dummies.

Theoretical Development

Data available in the Biomechanics Data Base consists of digitized time signals of acceleration taken from a 12 accelerometer array in the thorax. In addition, either a triaxial or 9 accelerometer array of signals are available for the head. In some tests, triaxial accelerometers were mounted on the fourth thoracic vertebrae. Finally, in a number of cases, impact force-time signal measurements have been made.

Consider a system of N particles. The force acting on each particle i is found by summing all of the forces acting the particle (Greenwood, 1965).

$$m_i a_i = F_i + \sum_{j=1}^{N} f_{ij} \qquad [1]$$

where:

- m_i = mass of particle i
- a_i = acceleration of particle i
- F_i = total force on particle i that results from external forces on body of which particle i is a member
- f_{ij} = forces between particle i and other particles j comprising the structure

The F_i term will be referred to as the external force, and f_{ij} will be referred to as the internal force.

Now sum over all particles in the system to obtain

$$\sum_{i=1}^{N} m_i a_i = \sum_{i=1}^{N} F_i + \sum_{j=1}^{N}\sum_{i=1}^{N} f_{ij} \qquad [2]$$

Note that internal forces always occur in equal and opposite pairs, thus

$$\sum_{j=1}^{N}\sum_{i=1}^{N} f_{ij} = 0 \qquad [3]$$

Also note that the total external force F acting on the system is

$$F = \sum_{i=1}^{N} F_i \qquad [4]$$

Thus, by combining equations 2, 3, and 4, we see that

$$F = \sum_{i=1}^{N} m_i a_i \qquad [5]$$

In the analysis presented here it is assumed that the system (the thorax in the immediate case) may be discretized into a finite number of masses. Such an

assumption is often made when creating lumped parameter models, as in the case of the Lobdell model, or in the creation of impedance models. In this study it was assumed for frontal impacts that the thorax could be discretized into a sternal mass, and another mass at the spine representing the remainder of the thoracic mass. For lateral impacts, the thorax was discretized into three masses, a struck side rib mass, a spinal mass, and a far side rib mass. This discretization is, in part, based on available signals in the Biomechanics Data Base. For a side impact test, equation 5 reduces to:

$$F(t) = m_{nr}a_{nr}(t) + m_{sp}a_{sp}(t) + m_{fr}a_{fr}(t) \quad [6]$$

where:

$F(t)=$	impact force at time t
$a_{nr}(t)=$	acceleration of near rib at time t
a_{sp}, a_{fr}	similarly defined for spine and far rib respectively
m_{nr} =	mass of the near rib
m_{sp}, m_{fr}	similarly defined for spine and far rib respectively

The right side of equation [6] will be referred to as the mass acceleration force.

$$F(t)_{mass\ accel} = m_{nr}\ a_{nr}(t) + m_{sp}\ a_{sp}(t) + m_{fr}\ a_{fr}(t)$$

Equation [6] is then rearranged to calculate an error squared term using dynamic data from a test.

$$\varepsilon^2(t) = (F(t) - F(t)_{mass accel})^2 \quad [7]$$

where:

ε	an error term
$F(t)$	the measured force at time t during the crash event

A numerical optimizer, ZXMWD from the International Mathematical Scientific Library (IMSL), is used to determine values for the masses which minimize the summation of the error squared term over the length in time of the signal. In this manner, the effective masses are determined. This may be considered as a system which optimizes the masses by finding the greatest correlation coefficient with the force-time signal recorded during a test. The optimizer is constrained to a search space with a minimum effective mass of 0.227 kg (0.5 pounds) and a maximum of 36.36 kg (80.0 pounds) when analyzing side impact data, and for frontal impacts, a minimum of .04545 kg (0.1 pounds) and a maximum of 45.45 kg (100.0 pounds).

A similar approach is used with frontal data, except that only two accelerations, sternal and spinal are used, to calculate two corresponding masses. To check the validity of the algorithm, the calculated masses are then multiplied by the appropriate acceleration signal and summed at each point in time. This mass-acceleration force signal is then compared to the original measured force.

When this was done the measured force always had a longer period than the mass-acceleration force signals were able to duplicate, indicating that not all masses had been accounted for. It was theorized that the head was the unaccounted mass. To test this theory, the force signal used by the optimizer was modified to remove the "head force." This was accomplished by taking the head center of gravity acceleration, or the acceleration of the center of the 9 axis head accelerometer array, and finding the resultant head acceleration. A head mass of 4.545 kg (10 pounds) was assumed and multiplied by the resultant head acceleration to calculate a "head force." This head force was then subtracted from the thoracic force, and the resulting force signal was used by the optimizer. Figure 1 illustrates a typical match obtained before the head force was removed, while Figure 2 shows the match obtained for the same test when the head force was removed. Removal of "head force" resulted in a significant improvement in the ability of the mass-acceleration force signals to match the measured force signal for most frontal tests (the exception being tests with a Hybrid III dummy). However, with lateral tests using only the struck rib and spinal accelerations, the period of the mass-acceleration force signal was still significantly shorter than the measured force signal, again implying that not all masses had been accounted for. The system was modified to now perform the force balance with three accelerations (adding the far side rib acceleration) and to also calculate a far side rib mass. This

modification resulted in significant improvement in the agreement between the mass-acceleration force signal and the measured force signal. Figure 3 shows the agreement obtained from a side impact test using only the struck side rib and spine, while Figure 4 shows the agreement using three masses.

The head force was created because in most tests within the Biomechanics Data Base the head does not strike anything. Thus, all of the force necessary to stop the head must come from other parts of the body. Specifically, it was assumed that all of the force to stop the head arose from forces on the thorax. In contrast, the pelvis, lower extremities, and other parts of the body typically impact some part of the test fixture (e.g., knee bolsters, lap belts, side wall) during a test, and thus some of their mass is not "seen" by the thoracic force used in the analysis. It will be found later that the system was less successful calculating an effective mass for pendulum tests. This is believed to be due to significant portion's of the mass creating the impact force not being instrumented and thus not available for analysis. A major difference between sled tests and pendulum tests is that all of the impact force in a pendulum test comes through the thorax, while in a sled test the impact force is distributed over more body surfaces. In a pendulum test the mass of the pelvis and lower extremity is "seen" in the thoracic impact force, and the system tries to assign this mass to the thorax.

It should be noted that this system cannot calculate, nor is it affected by the connectivity of the masses. As formulated, the system cannot calculate viscous or elastic elements connecting the masses. Others have reported systems capable of determining connectivity as well as effective mass (Hollowell 1988, Radwan 1990), but those systems were not used here. This insensitivity to the elastic and viscous elements connecting the masses may seem counter-intuitive. While the system does not know, and cannot calculate the stiffness of the thorax, the accelerations measured and used in the analysis are affected by thoracic stiffness. For a given set of thoracic *effective* masses, a stiffer system results in changes in the acceleration response measured, as well as the measured impact force. Thus, the same effective mass is calculated, regardless of the stiffness. This occurs without any knowledge of the stiffness of the system, or how the masses are connected. Among the implications are that the amount of damage done to the rib cage as a result of an impact does not affect the ability of the system to calculate the effective mass. Of course, the measured accelerations may be affected by the amount of damage to the skeleton, and this could affect the resulting effective masses calculated.

A similar counter-intuitive consequence of this analysis is that effective mass is not a function of time. The truth of this assumption is shown in how well the mass acceleration force matches the measured force. If effective mass were a function of time, and it was assumed that effective mass is not a function of time (as was assumed here) a graph of the measured force and the mass acceleration force would show the two curves crossing significantly as the true effective mass varied with time. Examination of Figures 2 and 4, as well as Figure 5 shows that this was not the case, in general, and in those cases where there was significant error the cause is believed to be the instrumented sites not being sufficient to account for all of the effective mass.

Test Conditions Analyzed

During the period of the analysis described here, the Biomechanics Data Base contained data from more than 2600 tests. For every test with a cadaveric subject in which the necessary signals were available, and for every corresponding dummy test with the necessary signals, the effective mass was analyzed. Table 1 summarizes the conditions analyzed.

All signals used for this analysis, both accelerations and force curves, were processed in a similar manner to that used by Eppinger, et al. (1984). Specifically the data were filtered with an SAE Class 180 300 Hz Butterworth filter, followed by subsampling to a sampling rate of 1600 Hz, followed by a 100 Hz Finite Impulse Response (FIR) filter with a -50 Db stop band gain. The effect of filtering is discussed later in this paper. The signals used, and the associated assumption about the discretization of the thoracic masses, were as follows:

1) For side impacts, two sets of runs were made. The first used the upper rib (fourth rib) on the struck and far sides, and the lower spine (T-12) lateral acceleration. The force signal was from the upper load cell

from the University of Heidelberg tests, and the sum of the shoulder and thoracic load plates from the tests at Wayne State University. The pendulum tests used the same set of thoracic accelerations and the impactor force signal. The analysis was repeated using the lower rib (eighth rib) accelerometers and T-12 lateral acceleration. The tests using the SID (Side Impact Dummy, defined in 49 Code of Federal Regulations, Part 572) were analyzed with the same signals. However, the BioSID does not have a far side rib accelerometer. Thus, for the BioSID, the struck rib and spine were used for the analysis, and only two effective masses computed. In none of the side impact tests were spinal accelerations other than upper (T-1) or lower (T-12) spine available. Lower spine accelerations were used because these signals seemed to give "better" results (i. e., better agreement between measured and mass-acceleration curves).

2) For frontal tests, the lower sternal (LSX) and T-4 anterior-posterior accelerations were used with steering column or pendulum force. The lower sternal accelerometer is mounted at approximately the same level as T-4 and thus the two may be considered to lay at the same level of the thorax. When tests with the Hybrid III were analyzed, a lower sternal accelerometer was matched with the standard chest anterior-posterior accelerometer in the dummy mounted on the spine box. In many pendulum tests with human cadaveric subjects a T-4 signal was not available. In these cases T-12 was used with the lower sternum, and T-1 was used with the upper sternum.

Note that with the exception of some pendulum tests conducted by the University of Michigan Transportation Research Institute (UMTRI), all side impact tests were performed with the arms down. The effect of this is to include the mass of the arm in the effective mass of the thorax.

As previously discussed, a "head force" was calculated and subtracted from the force signal used in the analysis. In some cases head accelerations were not recorded or available. In such cases the analysis was run without removing the head force.

PRESENTATION OF RESULTS

Side Impact

Table 2 displays the results obtained using the upper ribs and T-12 from lateral sled tests using human cadaveric subjects. Table 3 shows similar results using lower ribs and T-12. In addition to displaying the effective mass of the three instrumentation sites, the tables also display the summation of the three, the total mass of the test subject, and the percentage of the total body mass represented by each of the effective masses. The percentages are an attempt to normalize the results to account for differences in body mass between the test subjects. The column labeled "average error" in Tables 2 and 3 contains a measure of how well the mass-acceleration force matched the measured force. This number is calculated by equation [8].

$$\text{Average Error} = \sum_{t=1}^{N} \frac{\left(1 - \frac{F_{\text{mass accel}}(t)}{F_{\text{measured}}(t)}\right)}{N} \qquad [8]$$

where:

N = the number of data points with a measured force greater than 25% of the maximum measured force. Data points where the measured force is less than 25% of the maximum are ignored

$F_{\text{mass accel}}$ as previously defined
F_{measured} measured force at time t

This Average Error term is a numerical measure of how well the mass-acceleration signal matched the measured force. The use of the 25% value in the calculation of N is arbitrary. In general, values of less than 15 represent excellent agreement, values of 15-35 represent good agreement, values of 35-50 represent marginal agreement, and values greater than 50 indicate poor agreement. These distinctions are arbitrary, and the difference between a test with an average error of 36 and another with an average error of 34 is not significant. The goodness of fit represented by these values is illustrated by Figure 5 where comparisons of the measured impact force and the mass acceleration force are shown for five tests. The average

error for each of the five is shown, spanning a range from 6.4 (test H-83-04D) which represents excellent agreement, to 74.4 (test CM30) which represents poor agreement.

At the bottom of each column in Tables 2 and 3 are the average value and standard deviation for that column.

Table 2 reveals that for the particular test conditions examined,the mass of the thorax is nearly equally distributed between the three instrumentation sites, with the far side rib having the greatest mass. Examination of Table 3 reveals that using the lower ribs results in a similar pattern of a more massive far side rib, with the struck side rib and spine nearly equal in magnitude. Other items to note from Tables 2 and 3 are the relatively large standard deviations of the averaged values for the effective masses, indicating, in part, the inherent human variability. Also note that the average total body mass of the test subjects was on the smaller side of normal (69.4 or 68.7 kg (152.6 or 151.2 lbs) versus a 75 kg or 165 lb human average).

Tables 2 and 3 show that the system calculated signals whose average error was 34.4 for the upper rib, and 32.4 for the lower rib. These values suggest that the resulting mass acceleration forces match well with the measured force. In some cases in Tables 2 and 3 average errors were as high as 51.8 indicating that in some cases using the two ribs and spine did not account for all of the mass creating an impact force.

Tables 4 and 5 reveal a similar analysis for the pendulum tests conducted by the University of Michigan Transportation Research Institute (UMTRI). In these tests as in the tests in Tables 2 and 3, the arms of the subject were down during the test. Table 4 shows the results for the upper ribs, and Table 5 shows the results for the lower ribs. While the average mass of the test subjects in Tables 4 and 5 is similar to the average mass in Tables 2 and 3, it can be seen that a larger percentage of the total body mass is represented by the thoracic effective mass in the pendulum tests (53-63%) compared to the sled tests (26-28%). While the effective mass of the struck side rib does not change between the two types of tests, the masses of the spine and far side rib are approximately 2-3 times greater in the pendulum tests compared to the sled tests. In the sled tests, the subject impacted a thoracic and pelvic reaction plate, while in the pendulum tests the subject was accelerated totally by the thoracic impact force. Thus, in a pendulum test, the system must assign the mass of the lower extremities and pelvis to the thoracic masses available. It is speculated that this difference resulted in a much larger portion of the total body mass, indeed, in excess of 50%, being attributed to the far side rib and spine.

Values of the average error in Tables 4 and 5 are comparable to, though higher than, values found in Tables 2 and 3, and in the case of the upper ribs the average of the average error indicates marginal agreement. The pattern of the lower ribs yielding better agreement than the upper ribs is found again.

Table 6 reveals the results of analysis of data from pendulum impacts run by UMTRI with the arms up. In these tests, lower rib lateral accelerations were not measured, nor were head accelerations. Since there were no head accelerations available, the "head force" adjustment to the impact force was not made. From Table 6 it can be seen that the struck rib mass is smaller than in Tables 2-5. This is as expected because the mass of the arm is not a factor in these tests. Table 6 also reveals that most of the mass of the thorax is equally distributed between the spine and the far side rib, as seen in Tables 2 - 5. The pattern seen in Tables 4 and 5 of the spine and far side rib being more massive in pendulum tests than in sled tests, and the thoracic mass being a much larger percentage of the total body mass is again seen in Table 6. All of these observations must be tempered with the observation that the average error in all of the tests in Table 6 is over 60, indicating poor agreement. This poor agreement is due to the existence of significant effective masses that were not instrumented (or included in the analysis), resulting in a force being created, but there not being an acceleration signal to which the system could assign a mass.

Comparison of Table 6 to Table 4 is particularly interesting. All tests in these tables were conducted by the same organization with similar or identical test equipment, and the same set of signals are analyzed. The distinguishing factor between the tests in these two tables is that test subjects in Table 4 had their arms down, while those in Table 6 had their arms up. Note again that the analysis in Table 6 produced an

average error of 62.3 (range of 52.2 to 68.8), which is considered poor agreement and indicating that not all masses had been accounted for. The average error in Table 4 is 37.4 (range of 22.4 to 47.1). While 37.4 is significantly better than 62.3, the average error term in Table 4 is still considered marginal. Comparison of the effective masses reveals that between the two test conditions the values for the spine and far side rib are close to each other (24.4% versus 23.1% for the spine, and 22.6% versus 21.4% for the far rib). However, the struck side rib effective mass approximately doubled when the arm is down and included in the thoracic effective mass (5.9% versus 2.7%). The average mass of the test subjects used was approximately the same (71.7 kg versus 68.8 kg or 157.8 pounds versus 151.4 pounds). Note that in three of the tests in Table 6 the calculated struck side rib mass is less than 0.5 kg (1.0 pound), and indeed in two of the cases the optimizer ran into its lower constraint on struck side rib mass (0.227 kg or 0.5 pounds). While the number of tests is limited, and the agreement between the calculated and measured force is marginal at best, comparison of Tables 4 and 6 suggests that having the arms down does not affect the effective mass of the spine and far side rib, and adds approximately 2.5 kg (5 pounds) to the effective mass of the struck side rib.

Side Impact Sled Tests With Dummies

The results of analysis of tests using SID are shown in Table 7. This data comes from a series of tests run by the University of Heidelberg which duplicate the side impact cadaveric tests that they conducted. Because only one dummy was used, and only one test for each condition was run, variability between tests and between dummies cannot be evaluated. Several interesting points can be observed by comparing Table 7 to Tables 2 and 3. While the SID provided repeatable answers, particularly between rigid wall tests, it appears that the effective mass of the struck side rib is a function of the test condition. This can be seen because the effective mass of the struck side rib increases significantly between rigid wall tests and the APR pad test. Table 7 also shows that the effective mass of the SID struck side rib is approximately the same as the struck rib mass value found in tests with human cadaveric subjects. The effective mass of the SID's spine is larger than the value found from tests with cadaveric test subjects, and the SID's far side rib effective mass is less than the average from tests with cadaveric test subjects. Note that for the SID, the average error was less than 15, indicating excellent agreement.

The BioSID is analyzed in Table 8 (for the upper ribs with the lower spine) and Table 9 (for the lower ribs with the lower spine). These tests were conducted by the Vehicle Research and Test Center as part of a program to evaluate an early prototype of the BioSID. This test series duplicates the sled tests run at the University of Heidelberg. The tests selected had the arms of the dummy down in order to provide comparability to the Heidelberg test results. Two different BioSIDs (dummy 1 and 2) were used in two different test conditions (27.4 kph (17 mph) Rigid Wall, 37 kph (23 mph) APR padded wall). The BioSID does not have a far side rib instrumentation site, so the data were analyzed with the system that calculates the effective mass in frontal impacts. This system was given the force on the thorax, and the acceleration of the struck side rib and the spine of the dummy.

The spine of the BioSID may be considered to represent the mass of both the spine and far side rib from the tests with cadaveric test subjects from Heidelberg. A total body mass of 75 kg (165 pounds) for the BioSID was assumed when calculating percentages of total body mass represented by the rib and spine. Examination of Tables 8 and 9 shows the BioSid to have an average struck side rib effective mass of between 4 and 4.5 kg (9 and 10 pounds, or 5-6% of total body mass), with an average effective spine mass of 24 kg (53 pounds or 32% of total body mass). These numbers can be compared to the cadaver averages of between 4 and 5 kg (8 to 11 pounds, or 5-7% of body mass) for the struck side rib, and 14-15 kg (32-33 pounds, or 21% of total body mass) for sum of the spine and far side rib mass. The thoracic effective mass represents 38% of the total body mass in the BioSID as compared to 26-29% in the human subjects tested at Heidelberg. This implies that while the struck side rib effective mass of the BioSID is close to the values found with the cadaveric subjects, the total thoracic mass and the spinal mass of the BioSID are larger than the thoracic and spinal masses found in the

tests with cadaveric test subjects. The average error for the BioSID analysis was between 15 and 17 indicating good to excellent agreement.

In order to evaluate the sensitivity of this analysis to test condition, and to evaluate the variability between dummies, two other sets of averages are calculated in Tables 8 and 9. The average value of the effective masses based on test condition are shown below the overall average. Note that as with the SID there seems to be a sensitivity of effective mass to the test condition. While the effective mass of the struck side rib does not differ significantly between test conditions, the effective mass of the spine decreased in the higher speed padded test (from approximately 26 kg (57 pounds) down to 19-21 kg (43-46 pounds)). Two different BioSIDs, numbers 1 and 2, were used in this test series. To evaluate the variability between dummies, the averages for each dummy were calculated and are displayed in Tables 8 and 9. As with the variability between test conditions, there does not appear to be a significant difference between the struck side rib effective mass values, but there is a significant difference between the values for the spine effective mass. It is worth noting that 3 out of the 4 tests done in the 37 kph (23 mph) APR padded condition used dummy 2 which had the lower spine effective mass value. Thus, it is not possible to tell if the change in spine effective mass is due to variation between dummies, or if it is caused by variation due to the test condition.

Frontal Impact With Cadaveric Test Subjects

The next impact direction considered is frontal. Wayne State University conducted a number of tests with cadaveric test subjects run on a sled with a non-venting airbag mounted on a rigid, non-stroking, horizontally mounted steering column. These tests were analyzed using the lower sternum and T-4 accelerations together with the load on the steering column. The results of this analysis are shown in Table 10 from which it may be observed that these test subjects were heavier than average (80 kg or 175 pounds). The sum of the sternal and spinal effective masses averages to 35% of the total body mass, with the sternum responsible for 4% of the total body mass, and the spine responsible for 31% of the body mass. The average error in these tests was 20.2 indicating good agreement with the measured force signal. Comparing Table 10 to Tables 2 and 3 (side impact sled tests with cadaveric subjects) implies that the thoracic effective mass may be greater in a frontal impact than in a side impact.

Table 11 displays the results using the same set of signals from tests run by California Injury Research Associates (CIRA). In the CIRA tests a cadaveric subject was seated in the driver's seat of a generic passenger compartment. The test subject was unrestrained, and impacted the steering assembly during the test. The load on the steering column was measured and used in this analysis. In the CIRA tests the total thoracic effective mass represents 24% of the total body mass, compared to 35% in the Wayne State airbag tests. The differences for the spinal effective masses, 31.4% for airbag versus 17.5% for CIRA, are particularly noteworthy. Note also that the average body mass for the CIRA test subjects is approximately 15 kg (over 30 pounds) less than the average for the Wayne State test subjects. While the change in effective masses between the two data sets may be due to changing test condition, other factors such as change in the weight of the test subjects may be important. Note that there are only 4 tests from the Wayne State airbag series as opposed to 12 from the CIRA test series, but the average error for the CIRA tests is high at 48, indicating marginal agreement, while the Wayne State tests had good agreement with an average error of 20.2. Again, the poorer agreement in the CIRA tests is an indication that not all accelerations from masses creating forces on the steering assembly were available for analysis. The higher average error in the CIRA tests, when compared to the good average error in the Wayne tests, implies that the load paths and resulting mass distributions were different between the two test conditions.

Frontal Impact Sled Tests With Hybrid III

CIRA also ran a Hybrid III in the same test series, and the results from these tests are shown in Table 12. When analyzing the Hybrid III, the lower sternal acceleration was used with the standard chest x (anterior-posterior) acceleration together with the steering column force. A mass of 75 kg (165 pounds) was assumed for the Hybrid III. Comparison of Table 12

to Table 11 (same test series but using cadaveric test subjects) shows that the Hybrid III has approximately the same total thoracic effective mass (21.3% for the Hybrid III versus 24.3% for the cadaveric subjects), but the distribution between the sternum and spine is different. In the cadaveric test subjects, 6.9% of the total body mass is at the sternum, and 17.5% is at the spine, while the Hybrid III has only 1.1% at the sternum and 20.2% at the spine. Thus, the spinal mass of the Hybrid III is close to the value observed in the tests with cadaveric test subjects, but the sternal mass of the Hybrid III is less than sternal mass derived from the cadaveric tests. The higher sternal mass from the cadaveric test subjects may be due to loading through the shoulder during the test. In this case the mass of the shoulder would be lumped in with the mass of the sternum. The average error for the CIRA Hybrid III runs is 33.6 indicating good agreement.

Examination of the signals used in the CIRA tests with the Hybrid III indicated that the adjustment for head force might be responsible for some of the differences between the mass-acceleration forces and the measured forces. To test this theory, all CIRA data, both tests with cadaveric and Hybrid III test subjects, were reanalyzed. In this second round of analysis, the optimizer attempted to match the measured force without adjusting by removing head force. The results of this analysis are shown in Tables 13 (for the cadaveric test subject) and 14 (for the Hybrid III). From Table 13, it can be seen that the average error for the Hybrid III tests was significantly reduced when no adjustment is made for the head force (26.4 without adjustment, 33.6 with head force removal). As expected, when there is no adjustment for head force the effective masses are higher. Now the total thoracic mass is 28.6% of the total body weight, with the sternum representing 0.8% of the total body weight, and the spine representing 27.9%. This is compared to 1.1% and 20.2% for the sternum and spine when the head force adjustment is made.

However, the adjustment for head force, or lack of head force adjustment did not seem to affect the ability of the system to match the measured force when considering the CIRA cadaver tests. The average error when the head force adjustment was made compared to the average error when the head force adjustment was not made are almost the same (46 vs. 48). As expected, removal of the head force resulted in a lowering of the total thoracic effective mass at both the sternum and the spine.

Frontal Impact Pendulum Tests With Cadaveric Test Subjects

The next tests considered were a series of pendulum impacts conducted by UMTRI. In these tests a steering wheel was mounted on the face of a pendulum impactor, and the impact was directed so that the bottom of the wheel impacted the abdomen at approximately the level of the navel. Each test subject experienced three impacts, each at a higher speed than the previous. There was not an accelerometer at T-4 so the two sets of signals that are analyzed are upper sternum (USX) with T-1, and lower sternum (LSX) with T-12. In these tests head accelerations were not available; thus the "head force" could not be subtracted from the force used in the analysis. The results of the analysis are shown in Table 15. In view of the location of the impact (bottom of the steering rim at approximately the same level as the navel), the LSX/T-12 signals are perhaps of more relevance. Overall with the LSX/T-12 signals, the thoracic effective mass was 45.4% of the total body mass, with 8.2% at the sternum and 37.2% at the spine. Note, however, that these numbers change when the USX/T-1 signals are used. Now the sternum at 20.9% is more massive than the spine at 16.6%. The differences between using the two sets of signals are further illustrated when comparing the values for two particular test subjects, 84E153 and 84E163. Note for example that for 84E153, the sternum is more than 4 times more massive using the upper sternum compared to the lower sternum. All conclusions on these pendulum tests from UMTRI must be tempered with an examination of the average error figures. Note that while the USX/T-1 gave a somewhat more accurate match than LSX/T-12 (55.9 vs. 45.4), both are marginal to poor matches. In considering the difference between the USX/T-1 and LSX/T-12 data sets for 84E153, note the particularly poor agreement (75) found with the LSX/T-12 data set. With such poor agreement it must be concluded that the set of signals selected (sternal and spinal anterior-posterior accelerations) did not

measure the response of the appropriate effective masses, and that other uninstrumented parts of the body were creating significant portions of the force measured on the steering wheel.

Calspan Corporation conducted a number of thoracic pendulum impacts. The results of analysis using the lower sternum and T-4 anterior-posterior acceleration are shown in Table 16. In these tests the average body mass was 72 kg (158 pounds), and the total thoracic effective mass was 20.7%. The sternal effective mass was 1.2% of the total body mass, and the spinal mass was 19.5%. What is particularly interesting about these results is how closely the Hybrid III data from the CIRA tests, shown in Table 12, matches the data from the Calspan pendulum tests. The average sternal effective mass is the same between the two sets of data, and the spinal effective mass is 19.5% for the human subjects run in a pendulum test at Calspan, compared to 20.2% for the Hybrid III sled tests. It is also interesting to note how the mass distribution changes for human cadaveric subjects between pendulum tests, such as those at Calspan, and in sled tests such as those at CIRA and/or Wayne State. However, the average error for the Calspan pendulum tests was 63.4 indicating poor agreement between the measured force and the mass-acceleration force because the appropriate accelerations were not included in the analysis (nor available).

The final set of data considered were pendulum tests conducted by UMTRI in the late 1970's using human cadaveric test subjects. Neither head acceleration nor T-4 acceleration signals were available from these tests. This necessitated the use of lower spine (T-12) acceleration with lower sternum acceleration, and the "head force" could not be removed from the pendulum force. The results of the analysis performed are shown in Table 17. The effective mass of the sternum is 1.1% of the total body mass, and almost all of the thoracic effective mass is concentrated at the spine. The total thoracic effective mass is 26.9% of the total body mass. Once again the average error indicates poor agreement between the measured and mass-acceleration force signals.

Effect of Filtering

All data used were filtered with a 100 Hz Finite Impulse Response (FIR) Filter. One of the advantages of this FIR filter is its very steep stopband gain. The filter effectively removes all frequencies above 189 Hz. Filtering was performed to remove frequency content considered unimportant but potentially "confusing" to the optimizer. However, if a very small effective mass existed it would have a higher frequency acceleration response, potentially above the 100 Hz cutoff of the filter.

To evaluate the possibility that filtering might change the answers, a sample of the tests analyzed were reanalyzed without filtering the data (except for filtering necessary to prevent aliasing when the analog signal was digitized). An attempt was made to include tests which had both large effective masses and tests with smaller effective masses. Tests for which the optimizer was able to find a good match (as measured by the Average Error parameter) as well as tests for which a marginal or poor match was found were included. Both frontal and side, pendulum and sled tests were analyzed. The results of this random sample are shown in Tables 18 (for side impact data) and Table 19 (for frontal impacts).

Examination of Table 18 shows the effect of filtering on the effective mass determination for side impact data. A total of 8 tests are analyzed. In general, there are no significant differences between the results found using filtered data and the results found with unfiltered data. It should be noted that for test 77T080 the struck side rib mass remained at 0.2 kg (0.5 pounds) when using either filtered or unfiltered data. The optimizer is constrained for side impact cases to a minimum mass of 0.2 kg (0.5 pounds). However, it is interesting to also note with 77T080 that even though the struck side rib mass did not change, the spinal effective mass is 3 times more massive using the filtered data compared to the unfiltered data. Note however that based on the Average Error values found the optimizer did a poor job matching the measured force curve from this test.

Table 19 shows the comparison between filtered and unfiltered data for frontal impacts. The same 100 Hz FIR filter was applied to the frontal data as was applied to the side impact data. The results are similar to the findings with the side impact data in that filtering did not generally make a significant difference in the effective masses computed. For one of the sled tests (WS3041, an airbag test), the effective mass of the sternum doubled when filtering was not performed, while the spinal effective mass in the test was reduced by a similar amount. In one of the frontal pendulum tests (CM39) the overall thoracic effective mass was reduced significantly at both the sternum and the spine.

DISCUSSION

Much of the information in Tables 2-17 is surprising. Among these findings is that the far side rib must be considered in any side impact thoracic analysis. A significant portion of the total thoracic effective mass is located at the far side rib. Furthermore, the analysis suggests that the total thoracic mass is nearly equally distributed between the three instrumentation sites - near rib, spine, and far rib. The data also suggest that the spine is less massive than the far side rib. With one exception, all analysis of the side impact tests was performed on tests with the arms down. Thus, the mass of the arm is included in the effective mass of the thorax, particularly the struck and far side ribs. Examination of the tests in which the arms were up supported the observation that the far side rib is important to consider in a side impact, and revealed that the struck side rib mass increased by 2.25 kg (5 pounds) (i.e., rib effective mass doubled) by including the arm.

The two side impact dummies examined, SID and BioSID, also revealed several surprising findings. The analysis showed that the effective struck rib mass of both the SID and BioSID is approximately the same as the effective struck rib mass seen in tests with human cadaveric subjects with their arms down. However, both devices appear to have an effective spinal mass that is larger than the value found in the tests with cadaveric test subjects.

Comparing pendulum tests to sled tests for both frontal and lateral tests shows that the total thoracic effective mass was significantly greater in the pendulum tests than it was in the sled tests, with pendulum tests showing smaller effective mass at the sternum. Among the differences between sled and pendulum tests are the loading paths. In a pendulum test, all loading is through the thorax, while in a sled test, the shoulder and arms are also loaded as well as the thorax. These differences in load paths illustrate that pendulum tests cannot be directly compared to sled tests. Note that in all pendulum tests, the average error figure indicated poor agreement between the measured and mass-acceleration force signals. This is believed to be due to the selected instrumentation sites not being sufficient to discretize the thoracic mass. In a pendulum test, all of the force needed to accelerate the body arises from a thoracic force, including the force due to the mass of the pelvis and lower extremity, but the system can only assign mass to the thoracic signals; thus, it is not unreasonable to see less agreement in the results from a pendulum test than a sled test. In a sled test, impact force arises from areas of the body other than the thorax contacting a reaction surfaces; thus the thoracic accelerations better account for the resulting force. That the selected instrumentation sites provide good agreement in many sled test conditions (which are believed to be more representative of the environment in a car during a crash) is evidence that when data from a pendulum test contradicts data from a sled test, the cause may be differences in test condition, rather than one test being invalid.

While the study suggests that the effective mass and mass distribution found with a pendulum test is different from that of a sled test, it may also be that effective mass and mass distribution are dependent on test condition. Comparison of the frontal sled tests to the side sled tests finds a different total thoracic effective mass. Similarly, a comparison of the Wayne State frontal airbag tests to the CIRA frontal unrestrained tests finds a different total thoracic effective mass, and a different distribution of the masses. The Wayne State data set is limited in size, and the results might change if more tests were available, but it is

conceivable that effective mass may change as a function of test condition. This is a consequence of the different load paths between different test conditions. For example, in an airbag test (such as the Wayne State tests), a greater percentage of the total body mass compared to an unrestrained tests (such as the CIRA tests) could be carried by the steering assembly. The degree to which a test device such as a crash dummy can mimic these changes in effective mass as a function of test condition is a measure of the dummy's biofidelity.

The effective masses calculated also differed from mass values commonly used in lumped parameter models, specifically the Lobdell model. The total thoracic mass in either frontal or lateral impacts seldom approached the 61 pounds used in Lobdell's model. The ratio of struck side rib and arm mass to spinal mass was significantly different in the tests reported here compared to the ratio in the Lobdell model. All of this is not to say the Lobdell model is incorrect. However, the model was developed to simulate a series of frontal pendulum tests conducted by Kroell at al. (1974), and its application to other areas of interest must be used with caution.

When crash dummies are designed and built, the goal is to build a mechanical device from discrete elements and masses that can simulate a human, whose thorax is a continuous medium. In the analysis here a number of acceleration signals measured from discrete points on the thorax were used to determine the corresponding *effective* mass that should be attributed to an accelerometer signal in order to produce the impact force measured. In different test situations, the body is loaded through different paths. This difference in load paths explains how the thoracic mass could vary between 16 and 79% of total body mass.

The system described here is a first attempt to determine effective mass from experimental acceleration and force data. While based on first principles of mechanics, the system varied in its ability to match the force used for the analysis. Usually, when the match was not good, it suggested that the masses selected for the analysis did not include all of the masses producing the impact force. The system is not directly affected by the connectivity of the different instrumentation sites in the thorax, nor can it determine the connectivity.

The sensitivity of the system to errors in the acceleration signals is not known. That there are some errors in every acceleration signal due to items such as accelerometer rotation and misalignment cannot be questioned. However, it is believed that the errors in the acceleration signals are small and of little consequence in a force balance.

SUMMARY

A system was developed for determining thoracic effective mass based on acceleration signals and an impact force signal recorded during a test. The system uses a numerical optimizer to determine masses which when multiplied by acceleration signals minimize the cumulative error squared in a force balance on the system.

Using this system, pendulum and sled tests which simulate side and frontal impact tests were compared and analyzed. Among the findings are that the total thoracic effective mass, as well as the distribution of effective mass, is different in a pendulum test compared to a sled test, and in a frontal test compared to a side test. These differences are believed to be due to different loading paths in pendulum versus sled, and frontal versus lateral tests. The Hybrid III, SID, and BioSID were analyzed and compared to similar tests using human cadaveric subjects. These results found that while the effective struck side rib mass of the side impact dummies was close to the value found in the tests with cadaveric test subjects, the spinal effective mass of the side impact dummies was larger than the value found from the tests with cadavers. The total thoracic effective mass of all dummies tended to be larger than the value found from human cadaveric test subjects. The sternal mass of the Hybrid III was found to be less than the cadaveric test value.

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Table 1 - Summary of Test Conditions Analyzed

Side Impacts

Using Left and Right Upper Ribs (4th rib) and Lower Spine (T-12) lateral accelerations. Except as noted all tests were with the arms down

27.4 and 37 kph (17 and 23 mph) tests run at University of Heidelberg; both padded and unpadded impact surfaces

24.1 and 32.2 kph (15 and 20 mph) tests run at Wayne State University simulating Heidelberg tests, all into unpadded walls

Pendulum tests run at University of Michigan Transportation Research Institute (UMTRI) with both arms up and arms down

Tests run at the Transportation Research Center simulating the Heidelberg tests using the BioSID

The same tests were used with Left and Right Lower Ribs (8th rib) and Lower Spine (T-12) accelerations

Frontal Impacts

48.3 kph (30 mph) tests into a non-venting airbag on a rigid steering column mounted horizontally; run by Wayne State University; using Lower Sternum, x component (anterior-posterior) (LSX) and T-4 accelerations

24.1, 33.8, 40.2, and 43.5 kph (15, 21, 25, and 27 mph) tests of unrestrained subjects (both human cadaveric and Hybrid III) impacting a steering column; run by California Injury Research Associates (CIRA); using Lower Sternum (LSX) and T-4 accelerations for the cadaveric subjects, and LSX and the standard chest accelerometer in the Hybrid III

Pendulum tests with a steering wheel mounted to the front of the impactor run by UMTRI; using Lower Sternum - T-12 accelerations, and Upper Sternum - T-1 accelerations; also circular impactor on pendulum run at UMTRI with Lower Sternum and T-12 acceleration

Pendulum tests conducted by CALSPAN using Lower Sternum and T-4 accelerations

Test	Test Type	Test (kph)	Speed (mph)	Struck Rib (kg)	Struck Rib (lbs)	Spine (kg)	Spine (lbs)	Far Rib (kg)	Far Rib (lbs)	Total Mass (kg)	Total Mass (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass: Thorax	Near Rib	Spine	Far Rib	Average Error
H-82-008	APR	37.0	23	7.9	17.4	12.6	27.8	15.9	35.0	36.5	80.2	99.1	218	36.8%	8.0%	12.8%	16.1%	30.1
H-82-012	RW	45.1	28	10.5	23.2	11.8	25.9	8.3	18.2	30.6	67.2	75.0	165	40.7%	14.1%	15.7%	11.0%	24.7
H-82-014	RW	37.0	23	3.4	7.5	5.0	10.9	5.9	13.0	14.3	31.4	61.4	135	23.2%	5.5%	8.1%	9.6%	45.4
H-82-018	RW	27.4	17	3.1	6.9	8.0	17.7	14.5	32.0	25.7	56.6	85.0	187	30.3%	3.7%	9.4%	17.1%	19.2
H-82-021	APR	37.0	23	6.4	14.1	5.6	12.3	21.7	47.8	33.7	74.1	99.1	218	34.0%	6.4%	5.7%	21.9%	43.2
H-82-022	APR	37.0	23	3.7	8.2	4.4	9.8	14.2	31.2	22.4	49.2	77.3	170	28.9%	4.8%	5.7%	18.4%	23.4
H-83-010	6ENS	27.0	16.8	1.4	3.2	6.5	14.2	6.7	14.8	14.6	32.2	55.9	123	26.2%	2.6%	11.5%	12.0%	49.6
H-83-012	6ENS	32.2	20	7.7	17.0	16.0	35.2	0.2	0.5	23.9	52.7	77.3	170	31.0%	10.0%	20.7%	0.3%	29.7
H-83-020	12ENS	32.2	20	3.9	8.7	4.0	8.7	5.5	12.0	13.3	29.4	52.3	115	25.5%	7.5%	7.6%	10.4%	30.5
H-84-008	2ENS	32.2	20	9.2	20.2	9.5	20.8	7.7	17.0	26.4	58.0	64.1	141	41.1%	14.3%	14.8%	12.1%	31.5
SIC02	RWPO6	32.2	20	2.0	4.3	1.9	4.1	3.0	6.5	6.8	14.9	49.5	109	13.7%	3.9%	3.8%	6.0%	51.8
SIC03	RWPO6	37.0	23	4.3	9.4	4.3	9.5	6.2	13.6	14.8	32.6	70.0	154	21.1%	6.1%	6.2%	8.8%	35.8
SIC05	RW	24.1	15	2.1	4.6	3.5	7.7	2.1	4.7	7.7	17.0	44.1	97	17.5%	4.7%	7.9%	4.8%	35.7
SIC06	RW	32.2	20	3.4	7.4	3.9	8.6	3.5	7.6	10.7	23.6	60.9	134	17.6%	5.5%	6.4%	5.7%	31.0
Sled	Average			4.9	10.9	6.9	15.2	8.2	18.1	20.1	44.2	69.4	152.6	27.7%	6.9%	9.7%	11.0%	34.4
	St Dev			2.8	6.1	4.0	8.7	5.9	13.0	9.3	20.4	16.6	36.4	8.3%	3.5%	4.6%	5.7%	9.5

LEGEND:

- RW - Rigid Wall Test
- RWPO6 - Rigid Wall With 15 cm (6 in) Pelvis Offset
- APR - APR Padded Wall Test (APR -- Association Peugot-Renault)
- 2ENS - 5 cm (2 In) Ensolite Padded Wall Test
- 6ENS - 15 cm (6 in) Ensolite Padded Wall Test
- 12ENS - 30 cm (12 in) Ensolite Padded Wall Test

Table 2 - Side Impact Sled Tests With Cadaveric Subjects Using Upper Ribs

Test	Test Type	Test (kph)	Speed (mph)	Struck Rib (kg)	Struck Rib (lbs)	Spine (kg)	Spine (lbs)	Far Rib (kg)	Far Rib (lbs)	Total Mass (kg)	Total Mass (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass: Thorax	Percent of Total Mass: Near Rib	Percent of Total Mass: Spine	Percent of Total Mass: Far Rib	Average Error
H-82-008	APR	37.0	23	3.3	7.2	6.4	14.1	13.5	29.8	23.2	51.0	99.1	218	23.4%	3.3%	6.4%	13.6%	30.1
H-82-014	RW	37.0	23	1.9	4.3	3.8	8.4	8.0	17.7	13.8	30.3	61.4	135	22.4%	3.2%	6.2%	13.1%	37.5
H-82-018	RW	27.4	17	0.9	2.1	8.3	18.2	17.1	37.5	26.3	57.8	85.0	187	30.9%	1.1%	9.7%	20.1%	22.8
H-82-019	RW	27.4	17	2.8	6.1	0.5	1.0	17.2	37.9	20.5	45.0	67.3	148	30.4%	4.1%	0.7%	25.6%	28.9
H-82-021	APR	37.0	23	4.0	8.9	10.4	23.0	14.1	31.0	28.6	62.9	99.1	218	28.9%	4.1%	10.5%	14.2%	16.7
H-82-022	APR	37.0	23	4.9	10.8	4.0	8.8	13.5	29.8	22.5	49.4	77.3	170	29.1%	6.4%	5.2%	17.5%	23.3
H-83-010	6ENS	27.0	16.8	1.0	2.2	7.1	15.7	4.6	10.2	12.8	28.1	55.9	123	22.8%	1.8%	12.8%	8.3%	28.2
H-83-012	6ENS	32.2	20	8.1	17.7	11.8	26.0	10.8	23.8	30.7	67.5	77.3	170	39.7%	10.4%	15.3%	14.0%	17.3
H-83-020	12ENS	32.2	20	0.2	0.5	5.1	11.2	5.7	12.5	11.0	24.1	52.3	115	21.0%	0.4%	9.7%	10.8%	43.9
H-84-008	2ENS	32.2	20	13.0	28.6	6.4	14.1	4.6	10.2	24.0	52.8	64.1	141	37.5%	20.3%	10.0%	7.2%	34.9
SIC02	RWPO6	32.2	20	3.0	6.7	1.5	3.2	5.1	11.2	9.6	21.1	49.5	109	19.4%	6.1%	2.9%	10.3%	40.6
SIC05	RW	24.1	15	1.9	4.2	3.1	6.7	2.7	6.0	7.7	16.9	44.1	97	17.4%	4.3%	6.9%	6.2%	46.0
SIC06	RW	32.2	20	4.5	9.9	2.9	6.3	2.5	5.6	9.9	21.8	60.9	134	16.3%	7.4%	4.7%	4.2%	40.3
SIC07	RW	24.1	15	3.3	7.3	7.7	17	2.0	4.5	13.1	28.8	75.0	165	17.4%	4.4%	10.3%	2.7%	43.5
Sled			Average	3.8	8.4	5.5	12.0	9.2	20.2	18.5	40.7	68.7	151.2	26.1%	5.6%	7.8%	12.7%	32.4
			St Dev	3.3	7.3	3.2	7.1	5.2	11.4	7.7	16.9	17.1	37.6	7.1%	5.0%	3.9%	5.7%	9.6

LEGEND:
- RW - Rigid Wall Test
- RWPO6 - Rigid Wall With 15 cm (6 in) Pelvis Offset
- APR - APR Padded Wall Test (APR -- Association Peugot-Renault)
- 2ENS - 5 cm (2 In) Ensolite Padded Wall Test
- 6ENS - 15 cm (6 in) Ensolite Padded Wall Test
- 12ENS - 30 cm (12 in) Ensolite Padded Wall Test

SIC05 - HEAD DATA WAS NOT USED TO ADJUST THE FORCE

Table 3 - Side Impact Sled Tests With Cadveric Subjects Using Lower Ribs

Table 4 - Side Impact Pendulum Tests With Cadaveric Subjects Using Upper Ribs -- Arms Down

Test	Test Type	Test (kph)	Speed (mph)	Struck Rib (kg)	Struck Rib (lbs)	Spine (kg)	Spine (lbs)	Far Rib (kg)	Far Rib (lbs)	Total Thorax Mass (kg)	Total Thorax Mass (lbs)	Subject Mass (kg)	Subject Mass (lbs)	Percent of Total Mass: Thorax	Near Rib	Spine	Far Rib	Average Error
82E006	RIG	6.9	4.3	0.8	1.8	7.2	15.9	5.8	12.7	13.8	30.4	51.8	114.0	26.7%	1.6%	13.9%	11.1%	22.4
83E085	RIG	12.6	7.8	5.9	12.9	3.8	8.3	23.5	51.7	33.1	72.9	71.8	158.0	46.1%	8.2%	5.3%	32.7%	36.8
83E086	4ENS	30.6	19.0	3.5	7.8	9.7	21.3	19.8	43.5	33.0	72.6	71.8	158.0	45.9%	4.9%	13.5%	27.5%	47.1
82E048	4ENS	30.6	19.0	5.5	12.0	36.4	80.0	16.3	35.8	58.1	127.8	86.8	191.0	66.9%	6.3%	41.9%	18.7%	41.9
83E106	RIG	10.1	6.3	6.6	14.5	36.4	80.0	17.3	38.0	60.2	132.5	76.4	168.0	78.9%	8.6%	47.6%	22.6%	39.0
	Average			4.5	9.8	18.7	41.1	16.5	36.3	39.7	87.2	71.7	157.8	52.9%	5.9%	24.4%	22.6%	37.4
	St Dev			2.1	4.6	14.6	32.0	5.9	13.0	17.4	38.3	11.4	25.0	18.2%	2.5%	17.0%	7.4%	8.3

LEGEND:
RIG - Rigid Flat Face Impactor
4ENS - 10 cm (4 in) Ensolite Padding on Impactor Face

Test	Test Type	Test (kph)	Speed (mph)	Struck Rib (kg)	Struck Rib (lbs)	Spine (kg)	Spine (lbs)	Far Rib (kg)	Far Rib (lbs)	Total Thorax Mass (kg)	Total Thorax Mass (lbs)	Subject Mass (kg)	Subject Mass (lbs)	Percent of Total Mass: Thorax	Near Rib	Spine	Far Rib	Average Error
82E006	RIG	6.9	4.3	3.7	8.1	14.9	32.8	1.5	3.3	20.1	44.2	51.8	114.0	38.7%	7.1%	28.8%	2.9%	23.0
83E085	RIG	12.6	7.8	0.2	0.5	23.7	52.2	22.4	49.2	46.3	101.8	71.8	158.0	64.5%	0.3%	33.0%	31.1%	54.4
83E086	4ENS	30.6	19.0	0.2	0.5	21.6	47.5	22.9	50.5	44.8	98.5	71.8	158.0	62.3%	0.3%	30.1%	31.9%	41.0
82E048	4ENS	30.6	19.0	7.0	15.5	36.4	80.0	21.0	46.3	64.5	141.8	86.8	191.0	74.2%	8.1%	41.9%	24.2%	22.3
83E106	RIG	10.1	6.3	7.5	16.6	35.5	78.2	13.1	28.8	56.2	123.6	76.4	168.0	73.6%	9.9%	46.5%	17.1%	27.8
	Average			3.7	8.2	26.4	58.1	16.2	35.6	46.4	102.0	71.7	157.8	62.7%	5.1%	36.1%	21.5%	33.7
	St Dev			3.2	7.0	8.3	18.3	8.2	17.9	15.0	32.9	11.4	25.0	12.9%	4.0%	7.0%	10.7%	12.3

LEGEND:
RIG - Rigid Flat Face Impactor
4ENS - 10 cm (4 in) Ensolite Padding on Impactor Face

Table 5 - Side Impact Pendulum Tests With Cadaveric Subjects Using Lower Ribs -- Arms Down

Test	Test Type	Test (kph)	Speed (mph)	Struck Rib (kg)	Struck Rib (lbs)	Spine (kg)	Spine (lbs)	Far Rib (kg)	Far Rib (lbs)	Total Mass (kg)	Total Mass (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass: Thorax	Percent of Total Mass: Near Rib	Percent of Total Mass: Spine	Percent of Total Mass: Far Rib	Average Error
76T065	RIG	15.3	9.5	3.6	7.9	3.1	6.7	14.7	32.3	21.3	46.9	95.0	209	22.5%	3.8%	3.2%	15.4%	52.2
77T071	RIG	15.6	9.7	6.6	14.5	18.6	40.9	27.3	60.0	52.5	115.4	80.9	178	64.8%	8.2%	23.0%	33.7%	66.1
77T074	RIG	15.3	9.5	0.4	0.9	11.9	26.3	9.7	21.3	22.0	48.4	53.6	118	41.0%	0.7%	22.3%	18.0%	67.0
77T077	RIG	21.9	13.6	0.2	0.5	16.2	35.6	16.7	36.7	33.1	72.8	73.6	162	44.9%	0.3%	22.0%	22.6%	57.2
77T080	RIG	21.9	13.6	0.2	0.5	18.4	40.5	7.1	15.7	25.8	56.7	40.9	90	63.0%	0.6%	45.0%	17.4%	68.8
		Average		2.2	4.9	13.6	30.0	15.1	33.2	30.9	68.1	68.8	151.4	47.3%	2.7%	23.1%	21.4%	62.3
		St Dev		2.5	5.6	5.8	12.8	7.0	15.4	11.5	25.4	19.3	42.5	15.6%	3.0%	13.3%	6.6%	6.4

(head data not used - arms up)

LEGEND: RIG - Rigid Flat Face Impactor

Table 6 - Side Impact Pendulum Tests With Cadaveric Subjects Using Upper Ribs -- Arms Up

Using Upper Ribs

Test	Test Type	Test (kph)	Speed (mph)	Struck Rib (kg)	Struck Rib (lbs)	Spine (kg)	Spine (lbs)	Far Rib (kg)	Far Rib (lbs)	Total Mass (kg)	Total Mass (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass: Thorax	Near Rib	Spine	Far Rib	Average Error
H-83-04D	RW	18.2	17	2.5	5.5	21.0	46.3	3.9	8.7	27.5	60.5	75.0	165	36.6%	3.3%	28.0%	5.3%	11.0
H-83-05D	APR	24.6	23	4.7	10.4	19.4	42.6	1.9	4.2	26.0	57.2	75.0	165	34.6%	6.3%	25.8%	2.5%	19.2
H-83-06D	RW	24.6	23	2.2	4.8	19.3	42.5	3.1	6.8	24.6	54.1	75.0	165	32.8%	2.9%	25.8%	4.1%	12.9
	Average			3.1	6.9	19.9	43.8	3.0	6.5	26.0	57.2	75.0	165	34.7%	4.2%	26.5%	4.0%	14.4
	St Dev			1.1	2.5	0.8	1.7	0.8	1.8	1.2	2.6			1.6%	1.5%	1.1%	1.1%	3.5

Using Lower Ribs

Test	Test Type	Test (kph)	Speed (mph)	Struck Rib (kg)	Struck Rib (lbs)	Spine (kg)	Spine (lbs)	Far Rib (kg)	Far Rib (lbs)	Total Mass (kg)	Total Mass (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass: Thorax	Near Rib	Spine	Far Rib	Average Error
H-83-04D	RW	16	15	3.5	7.6	19.4	42.6	4.0	8.9	26.9	59.1	75.0	165	35.8%	4.6%	25.8%	5.4%	6.4
H-83-05D	APR	21.4	20	4.3	9.4	18.1	39.9	3.4	7.5	25.8	56.8	75.0	165	34.4%	5.7%	24.2%	4.5%	20.3
	Average			3.9	8.5	18.8	41.3	3.7	8.2	26.3	57.9	75.0	165	35.1%	5.2%	25.0%	5.0%	13.4
	St Dev			0.4	0.9	0.6	1.4	0.3	0.7	0.5	1.2			0.7%	0.5%	0.8%	0.4%	7.0

LEGEND:

RW - Rigid Wall Test
APR - APR Padded Wall Test

Table 7 - Side Impact Sled Tests With SID

Dummy Number	Test	Test Type	Test (kph)	Speed (mph)	Struck Rib (kg)	Struck Rib (lbs)	Spine (kg)	Spine (lbs)	Effective Thoracic Mass Total (kg)	Effective Thoracic Mass Total (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass: Thorax	Percent of Total Mass: Near Rib	Percent of Total Mass: Spine	Average Error
2	483	RW	27	17	3.1	6.8	26.5	58.2	29.5	65.0	75	165	39.4%	4.1%	35.3%	18.8
2	484	RW	27	17	4.4	9.7	25.9	56.9	30.3	66.6	75	165	40.4%	5.9%	34.5%	19.8
1	485	RW	27	17	4.1	9.1	26.7	58.7	30.8	67.8	75	165	41.1%	5.5%	35.6%	16.9
1	486	RW	27	17	4.5	9.8	25.3	55.7	29.8	65.5	75	165	39.7%	5.9%	33.8%	16.8
2	500	RW	27	17	3.3	7.3	26.5	58.4	29.9	65.7	75	165	39.8%	4.4%	35.4%	20.9
1	504	RW	27	17	4.5	9.9	24.8	54.5	29.3	64.4	75	165	39.0%	6.0%	33.0%	16.5
1	431	RW	37	23	3.6	8.0	25.6	56.3	29.2	64.3	75	165	39.0%	4.8%	34.1%	15.9
2	501	APR	37	23	4.9	10.7	21.1	46.4	26.0	57.1	75	165	34.6%	6.5%	28.1%	16.7
2	502	APR	37	23	5.0	11.0	20.0	43.9	25.0	54.9	75	165	33.3%	6.7%	26.6%	18.5
2	503	APR	37	23	4.0	8.9	21.3	46.8	25.3	55.7	75	165	33.8%	5.4%	28.4%	16.6
1	505	APR	37	23	5.8	12.8	21.4	47.0	27.2	59.8	75	165	36.2%	7.8%	28.5%	14.5
Overall Average					4.3	9.5	24.1	53.0	28.4	62.4	75	165	37.8%	5.7%	32.1%	17.4
Standard Deviation					0.7	1.6	2.5	5.4	2.0	4.4			2.7%	1.0%	3.3%	1.8
RW Average					3.9	8.7	25.9	57.0	29.8	65.6	75	165	39.8%	5.3%	34.6%	18.3
Std. Dev					0.5	1.2	0.7	1.4	0.5	1.2			0.7%	0.8%	0.9%	1.7
APR Avg					4.9	10.9	20.9	46.0	25.9	56.9	75	165	34.5%	6.6%	27.9%	16.6
Std. Dev					0.6	1.4	0.6	1.2	0.8	1.9			1.1%	0.8%	0.8%	1.4
Dummy 1 Average					4.5	9.9	24.7	54.4	29.3	64.4	75	165	39.0%	6.0%	33.0%	16.1
Std. Dev					0.7	1.6	1.8	4.0	1.2	2.6			1.6%	1.0%	2.4%	0.9
Dummy 2 Average					4.1	9.1	23.5	51.8	27.7	60.8	75	165	36.9%	5.5%	31.4%	18.6
Std. Dev					0.7	1.6	2.8	6.2	2.3	5.0			3.0%	1.0%	3.7%	1.5

LEGEND: RW - Rigid Wall Test
APR - APR Padded Wall Test

Table 8 - Side Impact Sled Tests With BioSID Upper Ribs -- Arms Down

Dummy Number	Test	Test Type	Test Speed (kph)	(mph)	Struck Rib (kg)	(lbs)	Spine (kg)	(lbs)	Effective Thoracic Mass Total (kg)	(lbs)	Total Subject Weight (kg)	(lbs)	Percent of Total Mass Thorax	Near Rib	Spine	Average Error
2	483	RW	27	17	4.2	9.3	26.4	58.1	30.6	67.4	75	165	40.8%	5.6%	35.2%	16.0
2	484	RW	27	17	5.1	11.3	25.4	55.9	30.5	67.2	75	165	40.7%	6.8%	33.9%	17.1
1	485	RW	27	17	4.4	9.7	26.0	57.2	30.4	66.9	75	165	40.5%	5.9%	34.7%	14.6
1	486	RW	27	17	4.5	10.0	25.1	55.2	29.6	65.2	75	165	39.5%	6.1%	33.5%	15.9
2	500	RW	27	17	4.6	10.1	25.6	56.4	30.2	66.5	75	165	40.3%	6.1%	34.2%	15.4
1	504	RW	27	17	4.2	9.3	25.0	54.9	29.2	64.2	75	165	38.9%	5.6%	33.3%	17.9
1	431	RW	37	23	4.0	8.9	25.4	55.8	29.4	64.7	75	165	39.2%	5.4%	33.8%	13.3
2	501	APR	37	23	4.3	9.5	20.1	44.3	24.5	53.8	75	165	32.6%	5.8%	26.8%	15.4
2	502	APR	37	23	4.7	10.3	18.4	40.4	23.0	50.7	75	165	30.7%	6.2%	24.5%	15.3
2	503	APR	37	23	5.0	11.0	20.1	44.2	25.1	55.2	75	165	33.5%	6.7%	26.8%	14.6
1	505	APR	37	23	4.2	9.3	20.8	45.7	25.0	55.0	75	165	33.3%	5.6%	27.7%	13.1
Overall Average					4.5	9.9	23.5	51.6	28.0	61.5	75	165	37.3%	6.0%	31.3%	15.3
St Dev					0.3	0.7	2.8	6.2	2.8	6.1			3.7%	0.4%	3.8%	1.4
17 RW Avg					4.5	9.8	25.6	56.3	30.0	66.2	75	165	40.1%	6.0%	34.1%	16.2
St Dev					0.3	0.7	0.5	1.1	0.5	1.2			0.7%	0.4%	0.7%	1.1
23 APR Avg					4.6	10.0	19.8	43.7	24.4	53.7	75	165	32.5%	6.1%	26.5%	14.6
St Dev					0.3	0.7	0.9	2.0	0.8	1.8			1.1%	0.4%	1.2%	0.9
Dummy 1 Average					4.3	9.4	24.4	53.8	28.7	63.2	75	165	38.3%	5.7%	32.6%	15.0
St Dev					0.2	0.4	1.9	4.1	1.9	4.2			2.5%	0.2%	2.5%	1.8
Dummy 2 Average					4.7	10.3	22.7	49.9	27.3	60.1	75	165	36.4%	6.2%	30.2%	15.6
St Dev					0.3	0.7	3.2	7.1	3.2	7.0			4.3%	0.4%	4.3%	0.8

LEGEND: RW - Rigid Wall Test
APR - APR Padded Wall Test

Table 9 - Side Impact Sled Tests With BioSID Using Lower Ribs -- ArmsDown

Test	Test Type	Test (kph)	Speed (mph)	Sternum (kg)	Sternum (lbs)	Spine (kg)	Spine (lbs)	Total Mass Thorax (kg)	Total Mass Thorax (lbs)	Total Mass Subject (kg)	Total Mass Subject (lbs)	Percent of Total Mass Thorax	Percent of Total Mass Sternum	Percent of Total Mass Spine	Average Error
WS3032	ABG	48	30	3.5	7.8	21.8	48.0	25.4	55.8	96.4	212	26.3%	3.7%	22.6%	23.5
WS3035	ABG	48	30	1.0	2.1	34.6	76.2	35.6	78.3	74.1	163	48.0%	1.3%	46.7%	26.2
WS3040	ABG	48	30	3.4	7.5	17.2	37.9	20.6	45.4	87.7	193	23.5%	3.9%	19.6%	15.3
WS3041	ABG	48	30	4.1	9.1	22.2	48.9	26.4	58.0	60.9	134	43.3%	6.8%	36.5%	15.7
Overall Average				3.0	6.6	24.0	52.8	27.0	59.4	79.8	175.5	35.3%	3.9%	31.4%	20.2
				1.2	2.7	6.5	14.2	5.4	11.9	13.5	29.7	10.6%	2.0%	10.9%	4.8

LEGEND: ABG - AIR BAG

Table 10 - Frontal Impact Sled Tests with Air Bag -- Cadaveric Test Subjects

Table 11 - CIRA Frontal Impact Sled Tests with Cadaveric Subjects

Test	Test Speed (kph)	Test Speed (mph)	Sternum (kg)	Sternum (lbs)	Spine (kg)	Spine (lbs)	Total Thorax Mass (kg)	Total Thorax Mass (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass Thorax	Percent of Total Mass Sternum	Percent of Total Mass Spine	Average Error
CI86008	43.5	27	2.3	5.1	13.8	30.3	16.1	35.4	68.2	150	23.6%	3.4%	20.2%	56.1
CI85020	24.1	15	4.3	9.5	5.2	11.4	9.5	20.9	54.5	120	17.4%	7.9%	9.5%	44.4
CI85023	24.1	15	1.9	4.2	17.6	38.7	19.5	42.9	77.3	170	25.2%	2.5%	22.8%	45.9
CI85022	24.1	15	5.1	11.2	2.3	5.0	7.4	16.2	78.6	173	9.4%	6.5%	2.9%	50.3
CI86002	45.1	28	3.9	8.5	11.9	26.2	15.8	34.7	53.2	117	29.7%	7.3%	22.4%	44.6
CI86003	43.5	27	5.3	11.6	11.1	24.4	16.4	36.0	66.8	147	24.5%	7.9%	16.6%	39.2
CI86005	43.5	27	4.0	8.8	7.6	16.7	11.6	25.5	76.4	168	15.2%	5.2%	9.9%	62.1
CI86007	43.5	27	3.1	6.8	13.2	29.0	16.3	35.8	57.3	126	28.4%	5.4%	23.0%	41.1
CI85024	33.8	21	6.4	14.0	17.0	37.5	23.4	51.5	70.5	155	33.2%	9.0%	24.2%	53.6
CI86001	40.2	25	4.4	9.6	13.5	29.8	17.9	39.4	58.2	128	30.8%	7.5%	23.3%	46.4
CI86004	43.5	27	7.8	17.1	10.2	22.5	18.0	39.6	59.1	130	30.5%	13.2%	17.3%	43.9
Overall Average			4.4	9.7	11.2	24.7	15.6	34.4	65.5	144	24.3%	6.9%	17.5%	48.0
Std Dev			1.6	3.6	4.5	9.9	4.4	9.6	9.0	20	7.1%	2.8%	6.8%	6.6

Test	Test (kph)	Speed (mph)	Sternum (kg)	Sternum (lbs)	Spine (kg)	Spine (lbs)	Total Thorax Mass (kg)	Total Thorax Mass (lbs)	Total Subject Wei ght (kg)	Total Subject Wei ght (lbs)	Percent of Total Mass Thorax	Percent of Total Mass Sternum	Percent of Total Mass Spine	Average Error
CI85005	34.0	21.1	2.8	6.1	3.2	7.1	6.0	13.2	75	165	8.0%	3.7%	4.3%	54.2
CI85006	34.0	21.1	1.9	4.2	5.2	11.4	7.1	15.6	75	165	9.5%	2.5%	6.9%	38.0
CI85007	34.0	21.1	1.4	3.0	16.1	35.5	17.5	38.5	75	165	23.3%	1.8%	21.5%	32.0
CI85008	34.0	21.1	0.8	1.8	11.8	25.9	12.6	27.7	75	165	16.8%	1.1%	15.7%	41.2
CI85009	34.0	21.1	0.2	0.4	9.2	20.3	9.4	20.7	75	165	12.5%	0.2%	12.3%	45.8
CI85011	34.0	21.1	0.0	0.1	10.9	24.0	11.0	24.1	75	165	14.6%	0.1%	14.5%	49.1
CI85012	34.0	21.1	1.9	4.1	19.7	43.4	21.6	47.5	75	165	28.8%	2.5%	26.3%	31.5
CI85013	34.0	21.1	0.0	0.1	18.7	41.1	18.7	41.2	75	165	25.0%	0.1%	24.9%	34.1
CI85014	34.0	21.1	0.0	0.1	10.5	23.1	10.5	23.2	75	165	14.1%	0.1%	14.0%	40.4
CI85016	24.1	15.0	0.8	1.8	26.3	57.9	27.1	59.7	75	165	36.2%	1.1%	35.1%	14.5
CI85017	42.6	26.5	2.6	5.7	11.0	24.2	13.6	29.9	75	165	18.1%	3.5%	14.7%	27.5
CI85018	40.2	25.0	0.5	1.2	17.7	39.0	18.3	40.2	75	165	24.4%	0.7%	23.6%	29.7
CI85015	25.4	15.8	0.5	1.0	26.0	57.3	26.5	58.3	75	165	35.3%	0.6%	34.7%	19.3
CI85019	40.2	25.0	0.4	0.9	13.7	30.1	14.1	31.0	75	165	18.8%	0.5%	18.2%	33.6
Overall Average			1.0	2.2	14.3	31.5	15.3	33.6	75	165	21.3%	1.1%	20.2%	33.6
Std Dev			0.9	2.0	6.7	14.7	6.4	14.1			8.1%	1.1%	8.2%	9.4

Table 12 - CIRA Frontal Impact Sled Tests with Hybrid III

Table 13 - CIRA Frontal Sled Tests with Cadaveric Subjects (Head Force Not Removed)

Test	Test (kph)	Speed (mph)	Sternum (kg)	Sternum (lbs)	Spine (kg)	Spine (lbs)	Total Thorax Mass (kg)	Total Thorax Mass (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass: Thorax	Percent of Total Mass: Sternum	Percent of Total Mass: Spine	Average Error
CI86008	43	27	3.4	7.5	15.5	34.2	19.0	41.7	68	150	27.8%	5.0%	22.8%	50.1
CI85020	24	15	5.5	12.0	8.3	18.2	13.7	30.2	55	120	25.2%	10.0%	15.2%	49.3
CI85023	24	15	2.5	5.4	20.8	45.8	23.3	51.2	77	170	30.1%	3.2%	26.9%	50.7
CI85022	24	15	5.8	12.7	15.9	34.9	21.6	47.6	79	173	27.5%	7.3%	20.2%	35.8
CI86002	45	28	4.1	9.0	17.0	37.3	21.0	46.3	53	117	39.6%	7.7%	31.9%	43.8
CI86003	43	27	8.0	17.5	19.3	42.4	27.2	59.9	67	147	40.7%	11.9%	28.8%	40.5
CI86005	43	27	3.4	7.5	11.7	25.8	15.1	33.3	76	168	19.8%	4.5%	15.4%	61.5
CI86007	43	27	4.8	10.6	14.8	32.6	19.6	43.2	57	126	34.3%	8.4%	25.9%	41.8
CI85024	34	21	8.3	18.2	23.0	50.6	31.3	68.8	70	155	44.4%	11.7%	32.6%	41.8
CI86001	40	25	4.4	9.6	13.5	29.8	17.9	39.4	58	128	30.8%	7.5%	23.3%	46.4
CI86004	43	27	7.8	17.1	10.2	22.5	18.0	39.6	59	130	30.5%	13.2%	17.3%	43.9
Overall Average			5.3	11.6	15.5	34.0	20.7	45.6	65	144	31.9%	8.2%	23.7%	46.0
Std Dev			1.9	4.2	4.3	9.4	4.9	10.7	9	20	7.0%	3.1%	5.9%	6.5

Test	Test Speed (kph)	Test Speed (mph)	Sternum (kg)	Sternum (lbs)	Spine (kg)	Spine (lbs)	Total Thorax Mass (kg)	Total Thorax Mass (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass: Thorax	Percent of Total Mass: Sternum	Percent of Total Mass: Spine	Average Error
CI85005	34	21	0.77	1.7	11.7	25.8	12.5	27.5	75	165	16.7%	1.0%	15.6%	33.6
CI85006	34	21	0.86	1.9	11.9	26.2	12.8	28.1	75	165	17.0%	1.2%	15.9%	30.3
CI85007	34	21	0.64	1.4	23.0	50.6	23.6	52.0	75	165	31.5%	0.8%	30.7%	22.2
CI85008	34	21	0.05	0.1	23.0	50.7	23.1	50.8	75	165	30.8%	0.1%	30.7%	36.3
CI85009	34	21	0.05	0.1	16.7	36.7	16.7	36.8	75	165	22.3%	0.1%	22.2%	33.0
CI85011	34	21	0.05	0.1	18.7	41.1	18.7	41.2	75	165	25.0%	0.1%	24.9%	40.3
CI85012	34	21	1.95	4.3	25.0	55.1	27.0	59.4	75	165	36.0%	2.6%	33.4%	23.6
CI85013	34	21	0.05	0.1	23.0	50.6	23.0	50.7	75	165	30.7%	0.1%	30.7%	30.6
CI85014	34	21	0.05	0.1	16.5	36.4	16.6	36.5	75	165	22.1%	0.1%	22.1%	33.8
CI85016	24	15	1.36	3.0	30.0	66.0	31.4	69.0	75	165	41.8%	1.8%	40.0%	12.3
CI85017	43	27	0.64	1.4	19.6	43.1	20.2	44.5	75	165	27.0%	0.8%	26.1%	23.0
CI85018	40	25	0.32	0.7	24.0	52.9	24.4	53.6	75	165	32.5%	0.4%	32.1%	22.2
CI85015	25	16	0.59	1.3	30.5	67.1	31.1	68.4	75	165	41.5%	0.8%	40.7%	11.1
CI85019	40	25	0.59	1.3	18.8	41.3	19.4	42.6	75	165	25.8%	0.8%	25.0%	24.3
Overall Average			0.57	1.3	20.9	46.0	21.5	47.2	75	165	28.6%	0.8%	27.9%	26.4
Std Dev			0.54	1.2	5.5	12.2	5.7	12.5			7.6%	0.7%	7.4%	8.4

Table 14 - CIRA Frontal Impact Sled Tests with Hybrid III (Head Force Not Removed)

Test	Signals Used	Test (kph)	Speed (mph)	Sternum (kg)	Sternum (lbs)	Spine (kg)	Spine (lbs)	Thorax Effective Mas (kg)	Thorax Effective Mas (lbs)	Total Subject Weight (kg)	Total Subject Weight (lbs)	Percent of Total Mass Thorax	Percent of Total Mass Sternum	Percent of Total Mass Spine	Average Error
84E142A	LSX/T-12	10.1	6.3	24.9	54.8	25.1	55.3	50.0	110.1	90.9	200	58.6%	11.8%	46.8%	49.4
84E153A	LSX/T-12	9.7	6.0	7.0	15.3	0.7	1.6	7.7	16.9	58.2	128	35.5%	8.0%	27.5%	70.4
84E153C	LSX/T-12	40.2	25.0	0.5	1.0	21.0	46.2	21.5	47.2	58.2	128	49.2%	0.2%	49.0%	79.6
84E163A	LSX/T-12	10.8	6.7	10.9	24.0	27.5	60.4	38.4	84.4	81.4	179	45.6%	11.6%	34.0%	32.1
84E163B	LSX/T-12	18.0	11.2	7.9	17.3	23.3	51.2	31.1	68.5	81.4	179	37.9%	9.2%	28.7%	48.0
84E142A	USX/T-1	10.1	6.3	23.9	52.5	17.0	37.3	40.8	89.8	90.9	200	45.2%	25.6%	19.6%	26.2
84E153A	USX/T-1	9.7	6.0	20.6	45.3	13.2	29.1	33.8	74.4	58.2	128	54.2%	33.4%	20.9%	34.1
84E153B	USX/T-1	18.0	11.2	5.1	11.3	8.9	19.6	14.0	30.9	58.2	128	24.6%	9.3%	15.4%	48.9
84E153C	USX/T-1	40.2	25.0	12.4	27.2	4.0	8.9	16.4	36.1	58.2	128	33.6%	16.9%	16.7%	68.9
84E163A	USX/T-1	10.8	6.7	15.9	35.0	15.2	33.5	31.1	68.5	81.4	179	39.5%	25.9%	13.6%	32.1
84E163B	USX/T-1	18.0	11.2	8.6	18.9	16.5	36.2	25.0	55.1	81.4	179	27.8%	14.3%	13.5%	62.2

		Sternum (kg)	Sternum (lbs)	Spine (kg)	Spine (lbs)	Thorax (kg)	Thorax (lbs)	Total (kg)	Total (lbs)	Thorax	Sternum	Spine	Average Error
Average 84E153	LSX/T-12	3.7	8.2	10.9	23.9	14.6	32.1	58.2	128.0	42.4%	4.1%	38.3%	75.0
Std Dev		3.3	7.2	10.1	22.3	6.9	15.2	0.0	0.0	6.8%	3.9%	10.8%	4.6
Average 84E153	USX/T-1	12.7	27.9	8.7	19.2	21.4	47.1	58.2	128.0	37.5%	19.8%	17.6%	50.6
Std Dev		6.3	13.9	3.8	8.3	8.8	19.4	0.0	0.0	12.4%	10.1%	2.3%	14.3
Average 84E163	LSX/T-12	9.4	20.7	25.4	55.8	34.8	76.5	81.4	179.0	41.7%	10.4%	31.3%	40.1
Std Dev		1.5	3.4	2.1	4.6	3.6	7.9	0.0	0.0	3.9%	1.2%	2.7%	8.0
Average 84E163	USX/T-1	12.3	27.0	15.8	34.9	28.1	61.8	81.4	179.0	33.7%	20.1%	13.6%	47.2
Std Dev		3.7	8.1	0.6	1.4	3.0	6.7	0.0	0.0	5.8%	5.8%	0.1%	15.1
Overall Av	LSX/T-12	10.2	22.5	19.5	42.9	29.7	65.4	74.0	162.8	45.4%	8.2%	37.2%	55.9
Std Dev		8.1	17.8	9.6	21.2	14.4	31.8	13.4	29.4	8.3%	4.2%	9.0%	17.0
Overall Av	USX/T-1	14.4	31.7	12.5	27.4	26.9	59.1	71.4	157.0	37.5%	20.9%	16.6%	45.4
Std Dev		6.5	14.3	4.6	10.2	9.5	20.8	13.6	29.8	10.1%	8.1%	2.8%	15.9

LEGEND:
- LSX - Lower Sternum - X Axis
- USX -Upper Sternum - X Axis
- T-12 - Lower Spine - X Axis
- T-1 - Upper Spine - X Axis

Table 15 - Frontal Cadaveric Pendulum Tests with Steering Wheel

Table 16 - CALSPAN Frontal Pendulum Tests With Cadaveric Subjects

Test	Test Type	Signals Used	Test (kph)	Speed (mph)	Sternum (kg)	(lbs)	Spine (kg)	(lbs)	Total Thorax Effective Mass (kg)	(lbs)	Total Subject Weight (kg)	(lbs)	Percent of Total Mass Thorax	Sternu	Spine	Average Error
CM47	Pen	LSX-T4	26	16	1.4	3.0	14.2	31.3	15.6	34.3	90.9	200	17.2%	1.5%	15.7%	69.1
CM30	Pen	LSX-T4	27	17	1.3	2.9	27.2	59.9	28.5	62.8	84.1	185	33.9%	1.6%	32.4%	74.4
CM37	Pen	LSX-T4	37	23	0.3	0.7	11.0	24.1	11.3	24.8	46.8	103	24.1%	0.7%	23.4%	57.4
CM48	Pen	LSX-T4	26	16	1.1	2.5	11.1	24.4	12.2	26.9	71.4	157	17.1%	1.6%	15.5%	69.0
CM54	Pen	LSX-T4	37	23	0.8	1.7	11.8	25.9	12.5	27.6	73.2	161	17.1%	1.0%	16.1%	71.0
CM39	Pen	LSX-T4	34	21	1.1	2.4	4.4	9.7	5.5	12.1	70.5	155	7.8%	1.5%	6.3%	37.1
CM46	Pen	LSX-T4	26	16	0.3	0.7	18.1	39.9	18.4	40.6	67.3	148	27.4%	0.5%	27.0%	66.0
		Average			0.9	2.0	14.0	30.7	14.9	32.7	72.0	158	20.7%	1.2%	19.5%	63.4
		St Dev			0.4	0.9	6.6	14.5	6.7	14.7	12.9	28	7.9%	0.4%	8.0%	11.8

LEGEND: Pen - Pendulum Test
LSX - Lower Sternum - X Axis
T4 - Middle Spine (4th Thoracic Vertebrae) - X Axis

Test	Test Type	Signals Used	Test (kph)	Speed (mph)	Sternum (kg)	(lbs)	Spine (kg)	(lbs)	Total Thorax Effective Mass (kg)	(lbs)	Total Subject Weight (kg)	(lbs)	Percent of Total Mass Thorax	Sternu	Spine	Average Error
76T056	Pen	LSX-T12	15.3	9.5	0.6	1.3	17.0	37.3	17.5	38.6	70.0	154	25.1%	0.8%	24.2%	54.7
77T068	Pen	LSX-T12	15.6	9.7	0.6	1.3	17.6	38.7	18.2	40.0	62.3	137	29.2%	0.9%	28.2%	68.7
77T083	Pen	LSX-T12	21.9	13.6	0.9	2.0	17.5	38.4	18.4	40.4	64.1	141	28.7%	1.4%	27.2%	55.5
77T086	Pen	LSX-T12	21.9	13.6	1.0	2.1	18.6	40.9	19.5	43.0	78.6	173	24.9%	1.2%	23.6%	65.8
		Average			0.8	1.7	17.6	38.8	18.4	40.5	68.8	151	26.9%	1.1%	25.8%	61.2
		St Dev			0.2	0.4	0.6	1.3	0.7	1.6	6.4	14	2.0%	0.2%	1.9%	6.2

LEGEND: Pen - Pendulum Test
LSX - Lower Sternum - X Axis
T12 - Lower Spine (12th Thoracic Vertebrae) - X Axis

Table 17 - UMTRI Frontal Pendulum Tests With Cadaveric Subjects

Table 18 - Effect of Filtering on Mass Determination -- Side Impact Using Upper Ribs

Test	Cond	Struck Rib (kg)	(lbs)	Spine (kg)	(lbs)	Far Rib (kg)	(lbs)	Total Mass (kg)	(lbs)	Total Subject (kg)	Weight (lbs)	Percent of Total Mass: Thorax	Near Rib	Spine	Far Rib	Average Error
H-82-014	20 RW	3.4	7.5	5.0	10.9	6.3	13.8	19.7	43.4	61.4	135	32.2%	5.5%	8.1%	10.2%	45.4
Unfiltered		3.5	7.8	5.3	11.7	6.0	13.2	20.0	44.0	61.4	135	32.6%	5.8%	8.7%	9.8%	53.7
H-82-018	15 RW	3.1	6.9	8.0	17.7	14.5	32.0	36.0	79.1	85.0	187	42.3%	3.7%	9.4%	17.1%	19.2
Unfiltered		3.4	7.5	8.7	19.1	14.0	30.8	36.4	80.1	85.0	187	42.8%	4.0%	10.2%	16.5%	23.2
H-82-021	20 APR	6.4	14.1	5.6	12.3	21.7	47.8	46.1	101.5	99.1	218	46.5%	6.4%	5.7%	21.9%	43.2
Unfiltered		5.0	10.9	8.2	18.1	12.4	27.2	34.9	76.8	99.1	218	35.2%	5.0%	8.3%	12.5%	50.5
H-82-022	20 APR	3.7	8.2	4.4	9.8	14.2	31.2	30.8	67.8	77.3	170	39.9%	4.8%	5.7%	18.4%	23.4
Unfiltered		3.1	6.8	5.3	11.7	10.6	23.3	26.2	57.7	77.3	170	33.9%	4.0%	6.9%	13.7%	42.2
82E006	4.3 Pen	0.8	1.8	7.2	15.9	5.8	12.7	19.8	43.5	51.8	114	38.1%	1.6%	14.0%	11.1%	22.4
Unfiltered		5.2	11.4	15.7	34.5	0.2	0.5	28.3	62.3	51.8	114	54.7%	10.0%	30.3%	0.4%	20.1
83E085	7.8 Pen	5.9	12.9	3.8	8.3	23.5	51.7	45.6	100.2	71.8	158	63.4%	8.2%	5.3%	32.7%	36.8
Unfiltered		5.6	12.4	3.4	7.4	23.6	52.0	44.9	98.8	71.8	158	62.5%	7.8%	4.7%	32.9%	36.1
82E048	19 PdPen	5.5	12.0	36.4	80.0	16.3	35.8	82.0	180.4	86.8	191	94.5%	6.3%	41.9%	18.7%	41.9
Unfiltered		4.9	10.7	36.4	80.0	14.4	31.7	78.7	173.2	86.8	191	90.7%	5.6%	41.9%	16.6%	46.6
77T071	9.7 Pend	6.6	14.5	18.6	40.9	27.3	60.0	73.3	161.3	80.9	178	90.6%	8.2%	23.0%	33.7%	66.1
Unfiltered		6.8	15.0	18.2	40	29.3	64.4	75.8	166.9	80.9	178	93.7%	8.4%	22.5%	36.2%	57.4
77T080	13.6 Pen	0.2	0.5	18.4	40.5	7.1	15.7	37.4	82.3	40.9	90	91.4%	0.6%	45.0%	17.4%	68.8
Unfiltered		0.2	0.5	5.7	12.6	8.0	17.7	20.3	44.6	40.9	90	49.5%	0.6%	14.0%	19.7%	78.4

Test	Cond	Sternum (kg)	(lbs)	Spine (kg)	(lbs)	Total Thorax Effective Mass (kg)	(lbs)	Subject (kg)	Weight (lbs)	Percent of Total Mass: Thorax	Sternum	Spine	Average Error
77T086	13.6 Pen	1.0	2.1	18.6	40.9	28.0	61.6	78.6	173	35.6%	1.2%	23.6%	65.8
Unfiltered		0.9	1.9	19.1	42.1	28.7	63.1	78.6	173	36.5%	1.1%	24.3%	71.7
WS3032	30 Air Bag	3.5	7.8	21.8	48.0	25.4	55.8	96.4	212	26.3%	3.7%	22.6%	23.5
Unfiltered		4.7	10.3	20.7	45.6	25.4	55.9	96.4	212	26.4%	4.9%	21.5%	30.6
WS3041	30 Air Bag	4.1	9.1	22.2	48.9	26.4	58.0	60.9	134	43.3%	6.8%	36.5%	15.7
Unfiltered		9.5	20.9	16.2	35.6	25.7	56.5	60.9	134	42.2%	15.6%	26.6%	23.0
CI86003	27 CIRA	5.3	11.6	11.1	24.4	16.4	36.0	66.8	147	24.5%	7.9%	16.6%	39.2
Unfiltered		4.4	9.6	11.7	25.8	16.1	35.4	66.8	147	24.1%	6.5%	17.6%	46.9
CI86005	27 CIRA	4.0	8.8	7.6	16.7	11.6	25.5	76.4	168	15.2%	5.2%	9.9%	62.1
Unfiltered		2.2	4.9	8.9	19.6	11.1	24.5	76.4	168	14.6%	2.9%	11.7%	65.9
CM30	17 Pend	2.2	4.8	18.6	40.9	29.2	64.3	84.1	185	34.8%	2.6%	22.1%	74.4
Unfiltered		1.9	4.1	12.2	26.9	19.6	43.2	84.1	185	23.4%	2.2%	14.5%	79.5
CM39	21 Pend	1.1	2.5	4.0	8.8	7.0	15.3	70.5	155	9.9%	1.6%	5.7%	37.1
Unfiltered		0.6	1.4	2.8	6.1	4.7	10.3	70.5	155	6.6%	0.9%	3.9%	56.7

Table 19 - Effect of Filtering on Mass Determination -- Frontal Impact

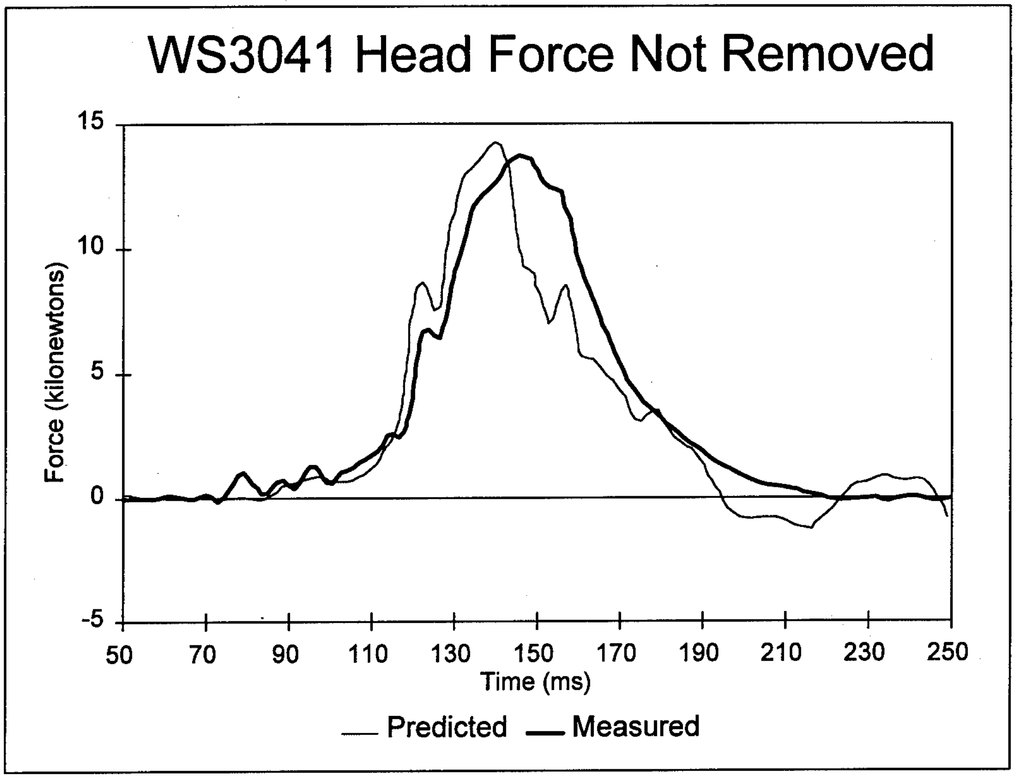

Figure 1 Measured and Predicted Forces **Without** Head Force Removal

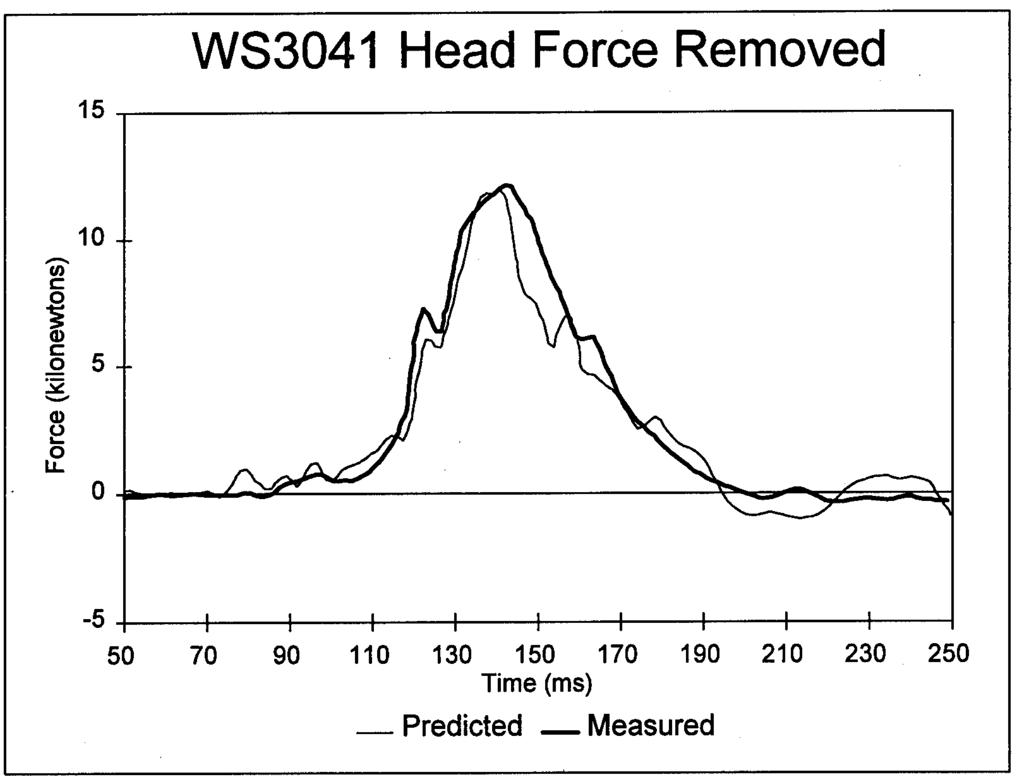

Figure 2 Measured and Predicted Forces **With** Head Force Removal

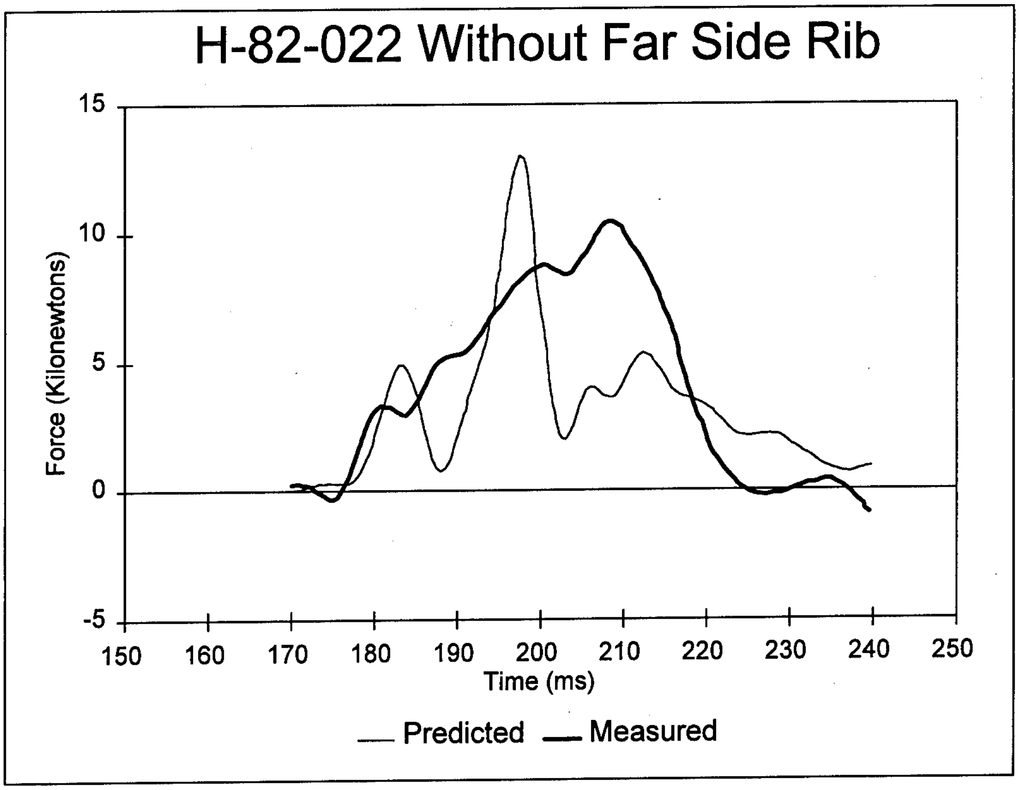

Figure 3 Measured and Predicted Forces Using **Only** Struck Side Rib and Spine

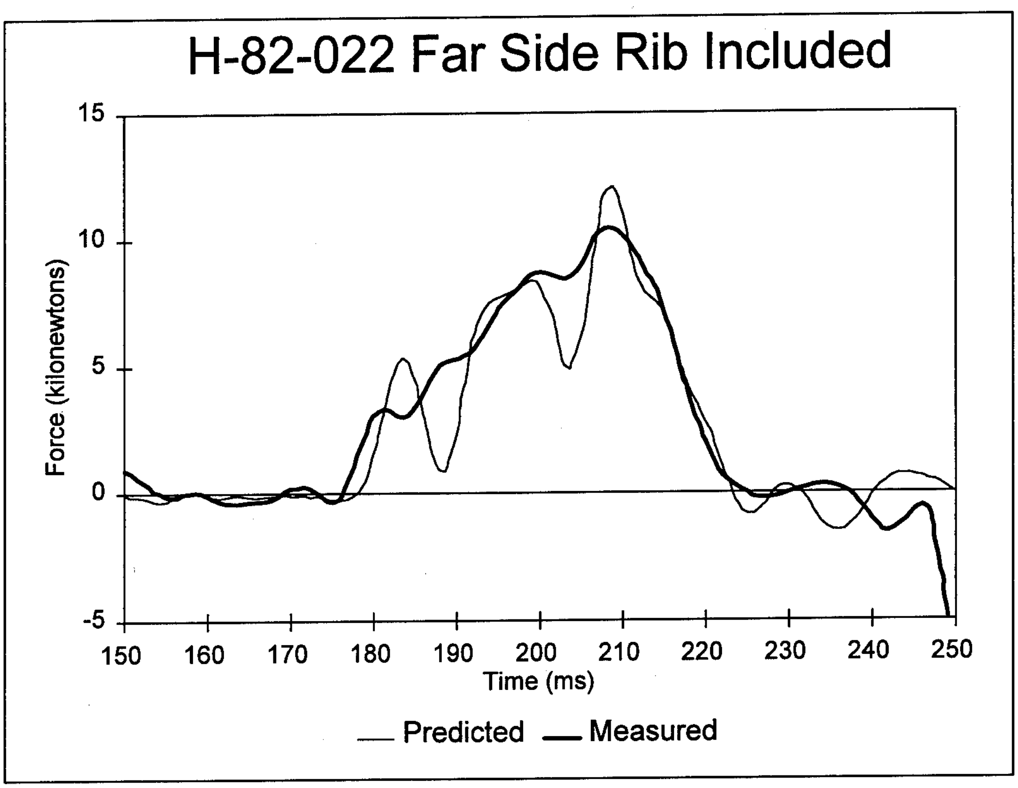

Figure 4 Measured and Predicted Forces Using Struck Side Rib, Spine, **and Far Side Rib**

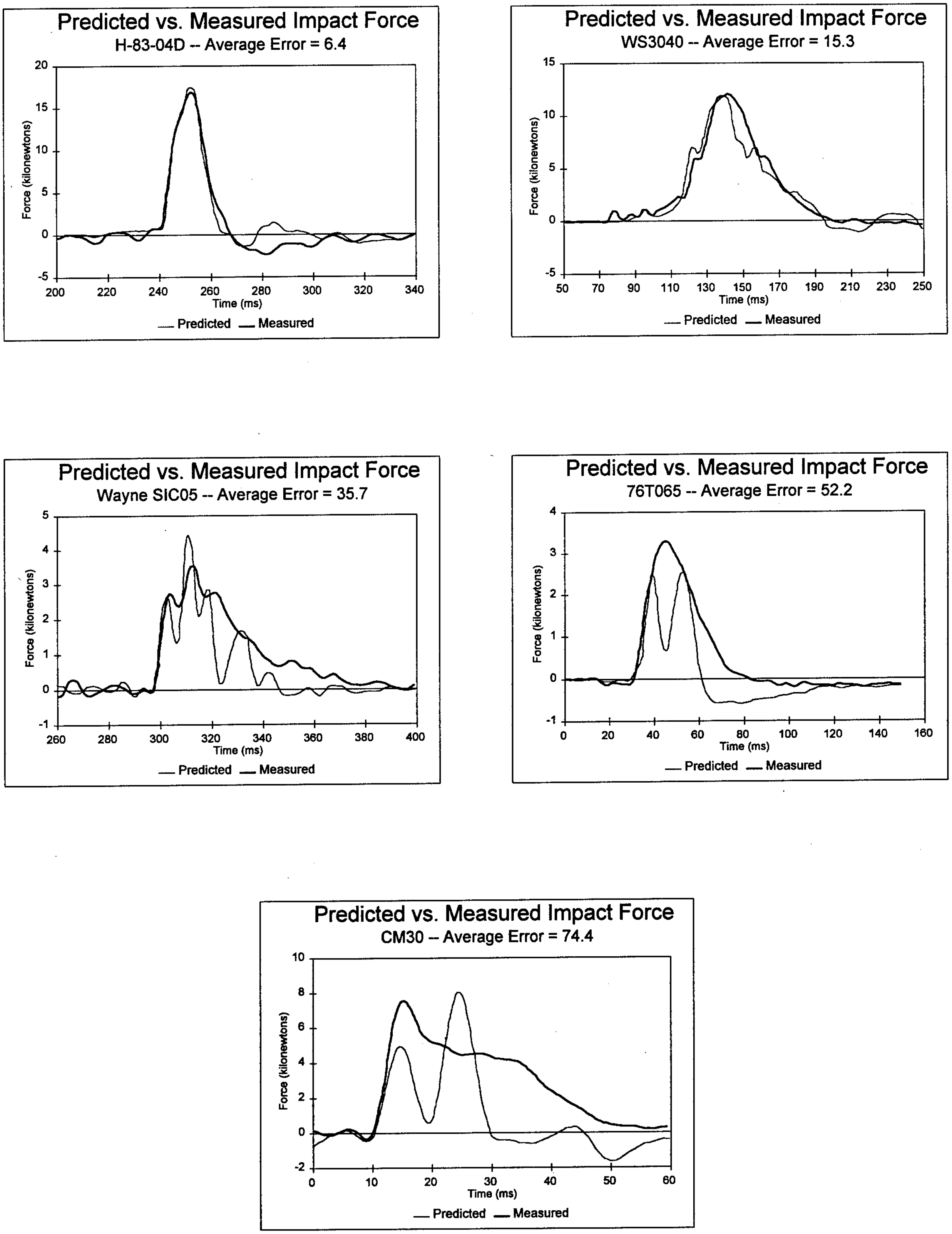

Figure 5 Illustration of Average Error Figures

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